# MAGNETIC AMPLIFIER CONTROL SYSTEM FOR SHIPBORNE RADAR ANTENNA DRIVE

William Bruce Tichenor

ELECTRONICS ENGINEERING REPORT

Lt. Cmdr. William Bruce Tichenor, U.S. Navy

# Magnetic Amplifier Control System
# For
# Shipborne Radar Antenna Drive

T47

WESTINGHOUSE ELECTRIC CORP.

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# INDEX

Page

I. INTRODUCTION . . . . . . . . . . . . . . . . . . . . . . . . 1

A. Statement of Problem. . . . . . . . . . . . . . . . . 1
B. Description of System. . . . . . . . . . . . . . . . 1

II. PROCEDURE. . . . . . . . . . . . . . . . . . . . . . . . . 4

A. Measurement of Component Characteristics . . . . 4
B. Design of Phase Detector and D-C Amplifier . . . 5
C. Calculation of Resonant Frequency of System and Determination of Bridge "T" Network Parameters . . . . . . . . . . . . . . . . . . . . 5
D. Measurement of Time Delays in System . . . . . . 8
E. Attempts to Compensate for Delays in System. . . 8
F. Frequency Response Analysis. . . . . . . . . . . . 8
G. Use of D-C Compensating Networks . . . . . . . . 8
H. Mathematical Analysis. . . . . . . . . . . . . . . 12

II. RESULTS. . . . . . . . . . . . . . . . . . . . . . . . . . 15

A. System Characteristics . . . . . . . . . . . . . . 15
   1. Steady State Torque and Speed Characteristics . . . . . . . . . . . . . . . . . . . . 15
   2. Magnetic Amplifier Transfer Characteristics. 15
B. Phase Detector and D-C Amplifier Characteristics. . . . . . . . . . . . . . . . . . . . . . . 15
C. Results of Experimental A-C Lead Nets. . . . . . 15
D. Results of Transient Measurements. . . . . . . . 22
E. Results in Reducing Delay in Controller. . . . . 22
F. Results of Frequency Response Analysis . . . . . 28
G. Results of D-C Compensating Network. . . . . . . 31

IV. SPECIAL MEASUREMENT TECHNIQUES. . . . . . . . . . . . . 31

V. CONCLUSIONS. . . . . . . . . . . . . . . . . . . . . . . . 36

VI. BIBLIOGRAPHY . . . . . . . . . . . . . . . . . . . . . . . 37

# I. INTRODUCTION

## A. Statement of Problem

The basic problem involved was to investigate the feasibility of the utilization of 6 previously designed magnetic reactors for control of the armature and field currents of the SPS-6 antenna drive motor with the future goal of adaptation of such a magnetic amplifier servo system as the antenna drive of the SPS-16 radar.

No rigid specifications of antenna control were defined. The antenna servo system was to be stable, and the output response to be reasonably rapid and to follow within approximately 1 degree at 2.5 rpm.

## B. Description of System

The initial system conceived was as follows:

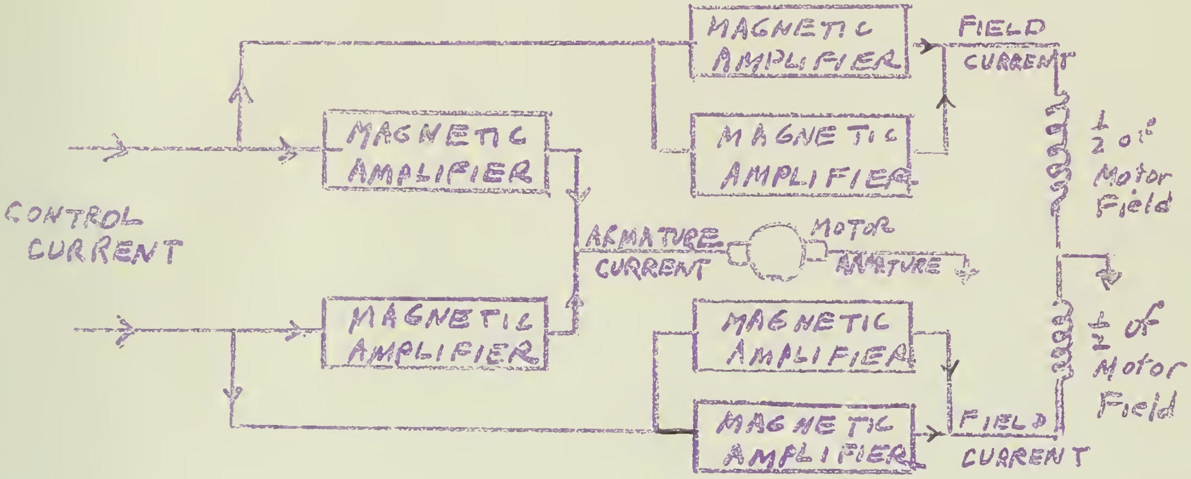


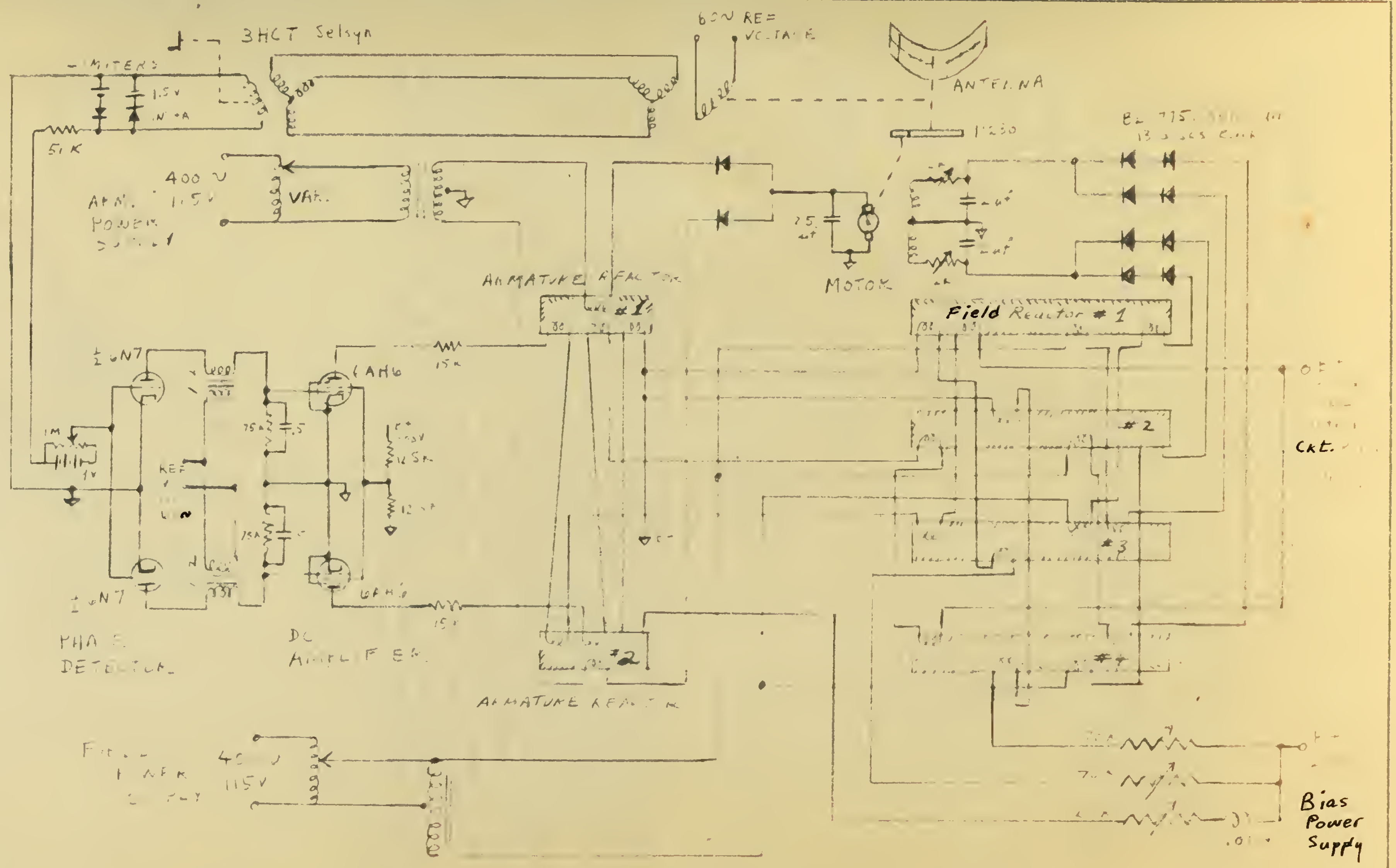
Figure 1(a)

The motor used was the original, 1/2 HP motor of the SPS-6 antenna drive, with a centertap added to the field windings. Both armature and field currents were to be controlled simultaneously, with armature current always in the same direction and the field current flowing through the appropriate half of the field winding to produce the desired direction of rotation.

The arrangement of winding is shown in detail in Figure 2. Refer to page 27 Figuring Book #41505 for direction and numbering of windings on cores. The armature reactors were wound with 3 windings of 370 turns each for control and the main current winding of 370 turns. Inductance of the armature control windings was approximately 11.3 henries each. Control current from either tube of the

d-c amplifier activated both of the armature reactors. Core material was Hipernik V.

The field reactors were smaller in size but contained a main current winding of 600 turns, 14 henries; a 600 turn, 14 henry winding for bias purposes; a 1640 turn, 104.5 henry winding for control purposes; and, in addition, an external winding of 16 turns so arranged as to form a push-pull effect, and therefore assist self saturation and gain of the magnetic amplifiers.



MAGNETIC AMPLIFIER SYSTEM AS FIRST DESIGNED FOR STUDY OF STABILITY CHARACTERISTICS (COMPENSATING NETWORKS NOT INCLUDED)

FIGURE 2

# I. PROCEDURE

## A. Measurement of Component Characteristics

1. The primary step to formulate and analyze the system was to obtain data on steady state speed and torque characteristics of the magnetic amplifiers, motor, and antenna connected as an open loop. A variable d-c power source was used to obtain various values of control current. Torque data was calculated from observed data in following manner.

   From d-c motor theory:

   1) $E_T = I_a R_a + E_c$

   2) $T = .703\, K\phi I_a$

   3) $E_c = S\phi K$

   Since from (3), $K\phi = E_c/S$

   and from (1), $E_c = E_T - I_a R_a$

   $\therefore T = .703\, I_a/S\, (E_T - I_a R_a$

2. The magnetic amplifier transfer characteristics (steady state) were determined by applying various values of d-c control currents to the reactors and measuring the output current resulting from an applied potential which would give approximately 2.5 RPM speed of rotation to the antenna. To prevent interaction of the field and armature reactors, the data was taken under static conditions with field or armature energized, motor not running. One dynamic test was made on the armature reactor with one field energized. Bias settings were such in each of the above to place the operating point at the knee of the saturation curve as shown in Figure 1.

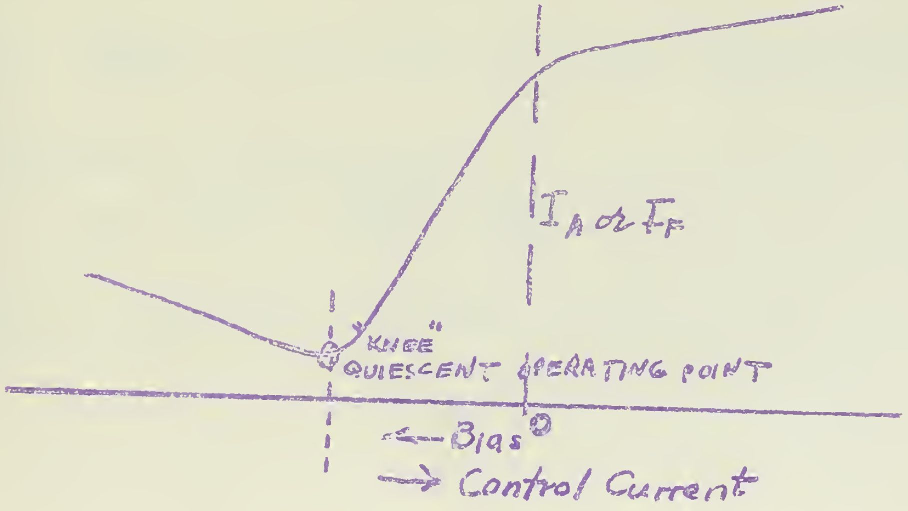


FIGURE 1 (b)

## II. B. Design of Phase Detector and D-C Amplifier

From data obtained in the foregoing procedure it was determined that a control current of 13 ma. would be the maximum needed for full saturation of the magnetic amplifiers and would give the full range of speed control desired. A phase detector and d-c amplifier was then designed to meet this requirement. Details are sketched in figure 2.

The purpose of the phase detector and d-c amplifier is to generate a control current which activates the magnetic amplifiers. The phase detector is biased near cutoff so that one side of it conducts heavily and the other is cut off depending upon the phase of the amplitude modulated error signal. Cut off of one side of the phase detector allows a bias to leak off of the RC grid lead of the next stage of the d-c amplifier allowing that half of the d-c amplifier to conduct heavily in proportion to magnitude of input signal. This conduction current is the Magnetic Amplifier control current.

Limiters consisting of selenium diodes 1N34A in series with 1.5 V batteries were placed across input to phase detector to protect against overloading inasmuch as the maximum error signal from the 3HCT synchro can be approximately 55 volts rms.

Upon completion of phase detector and its amplifier the system was formed as a closed loop as shown also in Figure 2. Meters were placed appropriately in the circuit to monitor individual field, armature, and control current circuits. Refer to pages 2-4, Figuring Book #41505.

## C. Calculation of Resonant Frequency of System and Determination of Bridge "T" Network Parameters.

$J_L = \frac{5300}{32.2}$ lbs. ft.$^2$ = 165 slug ft$^2$ (load inertia)

$J_{MO} = \frac{.17}{32.2} = 5.28 \times 10^{-3}$ slug ft.$^2$ (motor inertia)

Referred to output shaft

gear ratio $= \frac{3450}{15} = \frac{230}{1}$

$J_{MO} = 5.28 \times 10^{-3} \times (230)^2 = 280$ slug ft.$^2$

. C. Cont'd

Total moment of Inertia:

$$J = J_L + J_{MO} = 165 + 280 = 445 \text{ slug ft.}^2$$

Assuming 500 ft. lbs. max. wind torque,

$$\text{controller factor } K = \frac{\text{torque}}{\text{error}} = \frac{\frac{500}{1}}{57.3} = 28{,}600 \text{ ft. lbs./rad. error angle}$$

to follow within 1 degree.

Natural frequency of Motor and Antenna system:

$$\omega_n = \sqrt{K/J}$$

$$\omega_n = \sqrt{\frac{2.86 \times 10^4}{445}} = \sqrt{64.4} = 8.03 \text{ rad/sec.}$$
$$1.28 \text{ cycles/sec.}$$

It was observed that in closed loop shown in Figure 2, the antenna tended to oscillate at a very low frequency, approximately 1 cycle/sec. and, if gain were lowered, such oscillations would damp out after about 3 or 4 cycles. It was assumed therefore that the system was considerably underdamped with

$$\zeta \doteq .2$$

If a 10% decrease in torque is assumed for a speed increase of 2.5 rpm,

$$\text{Friction } F = \frac{500 \times .1}{2.5 \times \frac{2}{60}} = 191$$

$$\text{rel. friction } r = \frac{F}{2\,\zeta\,\omega_n J} = \frac{191}{2x.2x8.03x445} = .1236$$

If, to correct this oscillatory tendency, it is desired to insert an error plus derivative control network to shift the phase (envelope) of the amplitude modulated error signal carrier to compensate for the unwanted time delay causing the oscillation, the error network parameter would be

$$\omega_b = \frac{\omega_n}{2\,\zeta\,(1-r)} = \frac{1.28}{2x.2(1-\overset{.1236}{.06663})} = 3.44 \text{ cycles}$$

II. C. Cont'd

rel. frequency bandwidth

$$x_b = \frac{2\omega b}{\mu c} = \frac{2 \times 3.44}{60} = .114 \qquad P = \frac{2}{X_b} = \frac{2}{.114} = 17.5$$

where $\mu c$ = carrier frequency = 60 cycles.

Choosing a C = .01 μf for a bridged T network:

Series R of net is $R = \dfrac{P}{C\ \mu_c} = \dfrac{17.5}{.01 \times 10^{-6} \times 377} = 4.6$ megohms

Shunt R of net is $\dfrac{4.6 \times 10^6}{(17.5)^2} = 1500$ ohms

output of net for input of 1 volt ( = 1° error):

$$e_c = \frac{X_b^2}{2} = \frac{(.114)^2}{2} = .0065 \text{ volts rms.}$$

It was decided at this point to use a differentiating network, with a low pass filter to eliminate ripple (Refer to page 201, volume 25 Radiation Lab) and a pre-amplifier to feed the phase detector.

A two stage, 600 gain, 60 cycle center frequency, Audio Amplifier was designed in addition to a low pass filter. With the aid of a Technology Instrument Corporation Phase Meter "320-A" several a-c lead networks accounting for lead times of .012 to .046 seconds were constructed and centered carefully on 60 cycles for zero phase shift at the carrier frequency. Refer to pages 13-17, Figuring Book #41505 for details on these circuits. The general form of the bridged "T" network is shown in Figure 3.

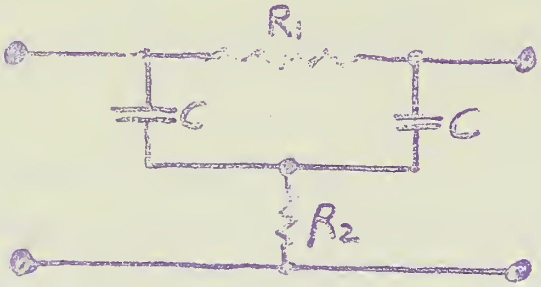


Figure 3

The above were placed in the closed loop system and changes of response noted.

## D. Measurement of Time Delays in System

In an attempt to establish the system time delays more accurately so as to reduce them and eliminate the need for critical lead networks, a triggering arrangement was devised whereby an impulse function could be applied to the system (open loop) and the transient response of various portions of the system photographed. A special slow sweep oscilloscope (Tektronix 512) and Polaroid Land Camera were used for this purpose.

In this way the actual delay time in the phase detector -- d-c amplifier, the magnetic amplifiers and in the field and armature circuits was measured.

## E. Attempts to Compensate for Delays in System

The measured delay information was used in two ways.

1) Favorable initial conditions giving fastest response of the magnetic amplifiers were utilized.

2) Knowing the actual transient delay in the circuit enabled further attempts at compensating for same.

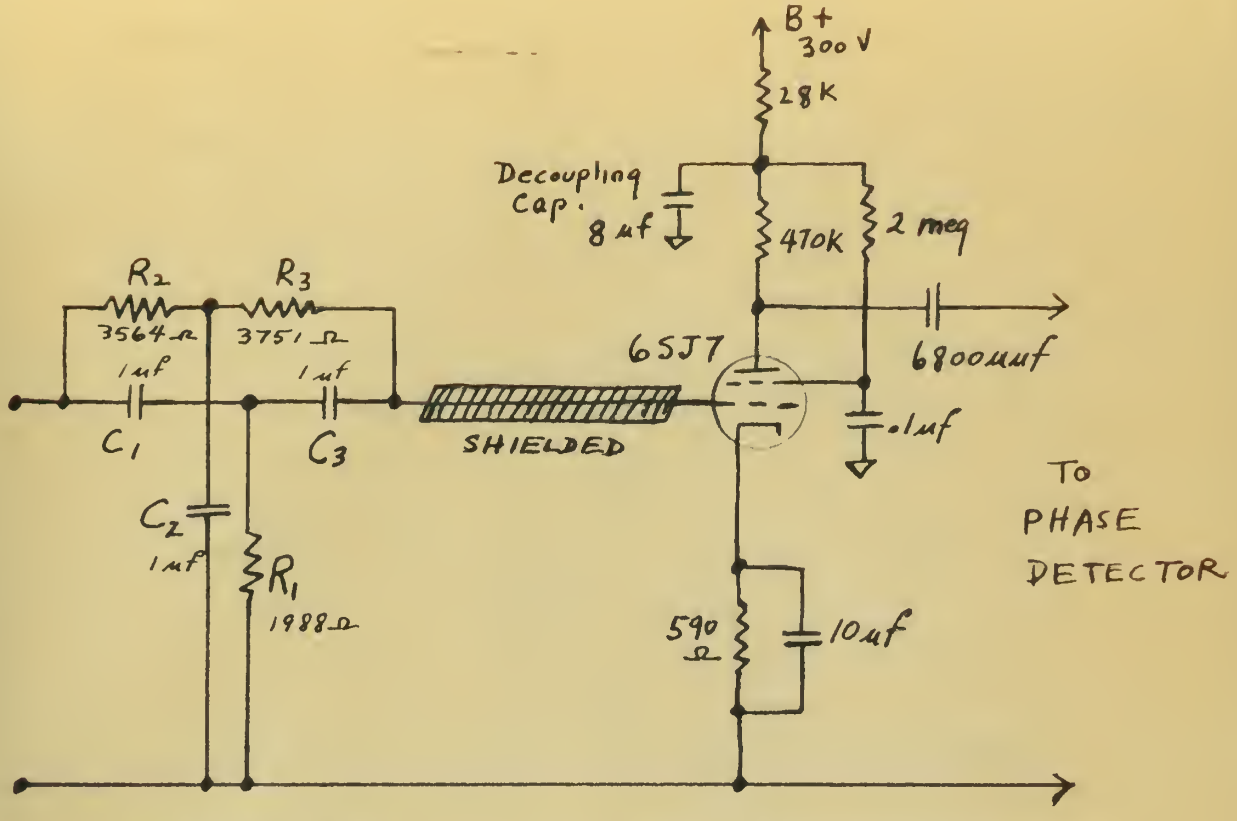
Another a-c lead network was constructed, this time a parallel T (Refer to Radiation Lab. Series Vol. 25) and for greater gain, to the exact specifications required by this known delay. A more sensitive a-c amplifier was designed also for use with this network and was linear over the required low frequency range. The combination network and amplifier is shown in Figure 4.

## F. Frequency Response Analysis

Closed loop response $(\frac{\theta_o}{\theta_i})$ to sinusoidal input of varying frequency was then determined in order to reshape properly the response curves of the system using d-c networks.

## G. Use of D-C Compensating Networks

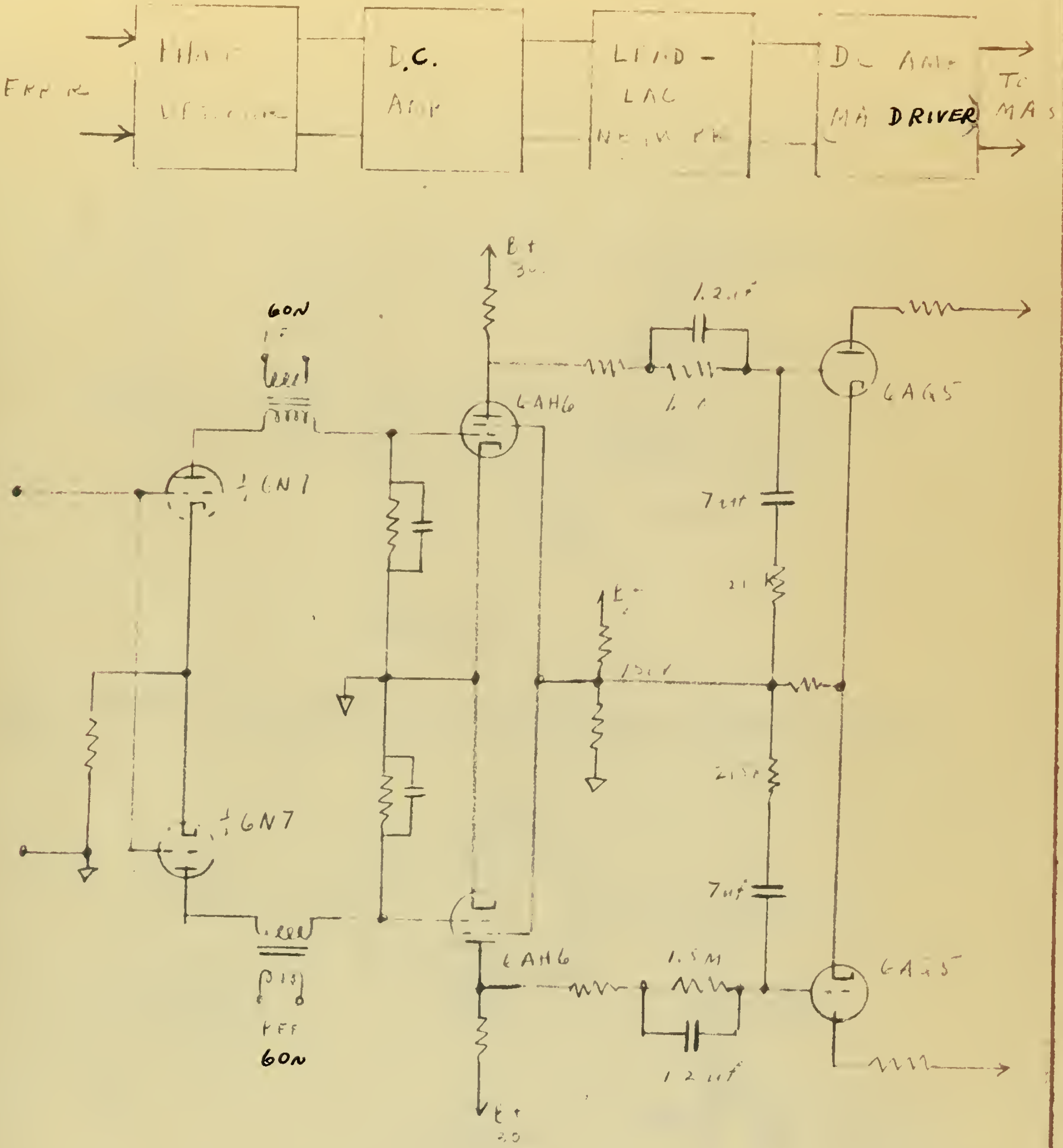
Based upon information determined from the preceding frequency response analyses, the system was modified as indicated in Figure 5 in order to use a d-c lag-lead network whose gain characteristics are approximately those shown in Figure 6.



PARALLEL "T"
A.C. LEAD NETWORK

A.C. AMPLIFIER
GAIN ≐ 157 at 60~

FIGURE 4.



USE OF D.C. COMPENSATING NETWORK

FIGURE 5

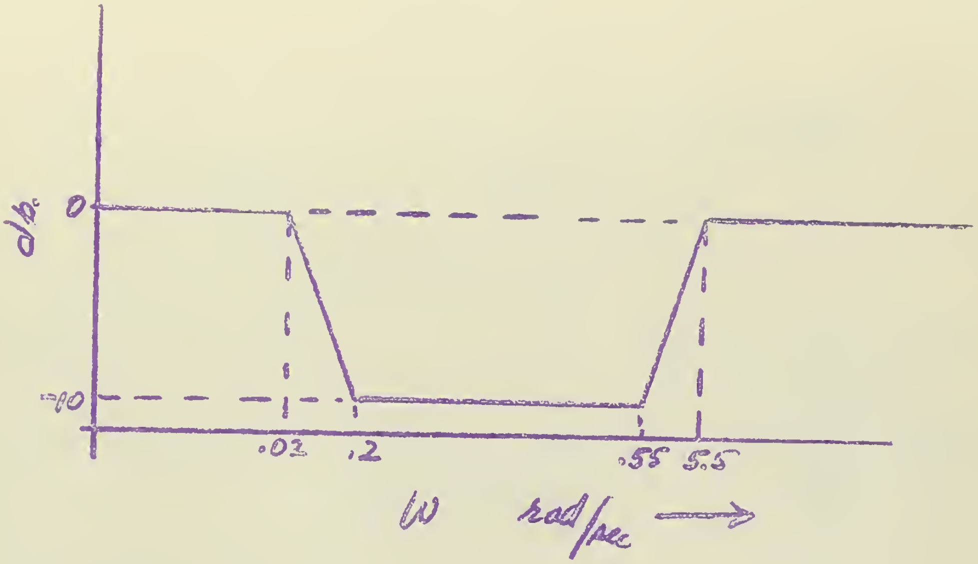


Figure 6

The network to produce above frequency response change is

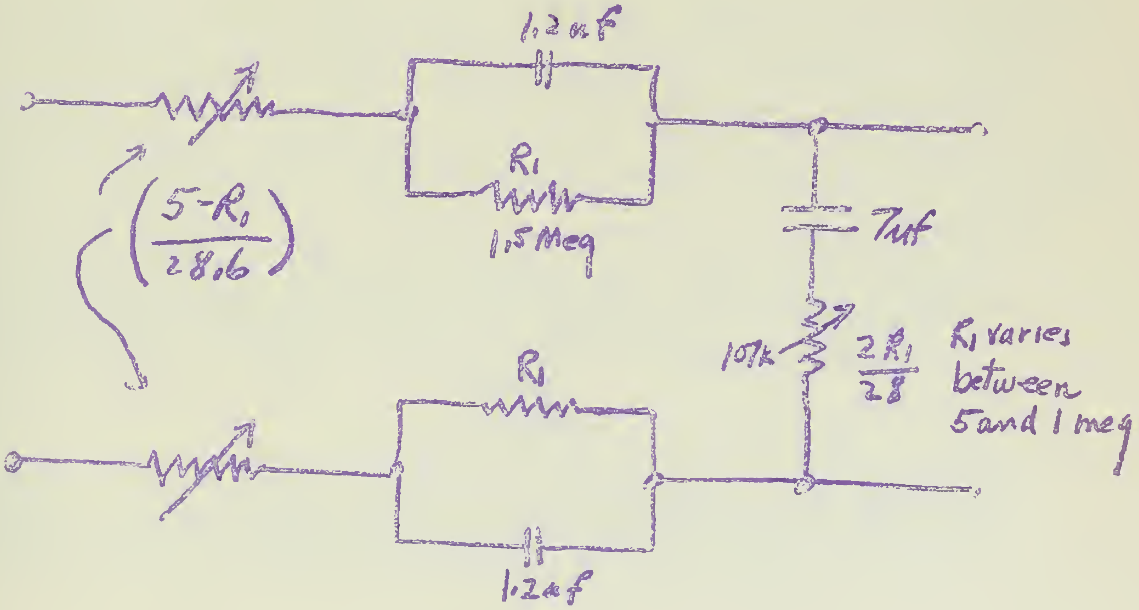


Figure 7.

## I. II. Mathematical Analysis

A very simplified diagram of the servo system is shown below in Figure 3. Electrical energy storages accounting for time delays are not included. Estimated "linear" transfer functions are indicated.

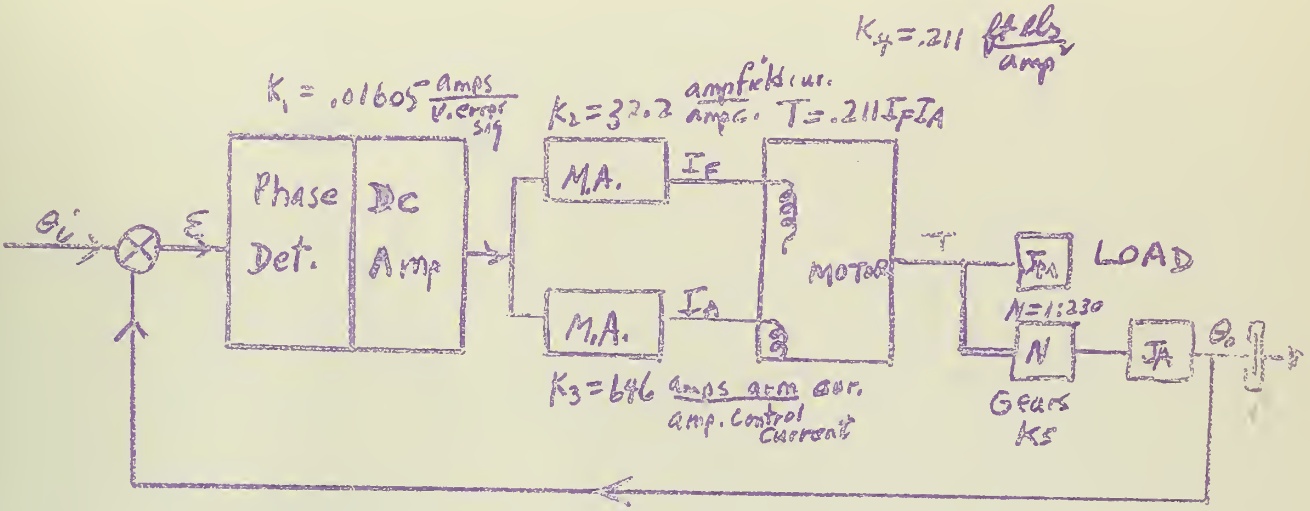

$K_4 = .211$ ft lbs / amp
$K_1 = .01605$ amps / v. error sig
$K_2 = 32.2$ amp field cur. / amp c.
$T = .211 I_F I_A$
Phase Det.
Dc Amp
M.A.
$I_F$
M.A.
$I_A$
MOTOR
T
$\theta_i$
$\varepsilon$
$J_{FA}$
LOAD
N=1:230
N
$J_A$
$\theta_o$
$K_3 = 646$ amps arm cur. / amp. control current
Gears
K5

Figure 3

An attempt at mathematical analysis was made and carried through using Laplace transform~~ers~~ after certain simplifying assumptions. The main difficulty encountered was the nonlinearity of the overall transfer function since torque is proportional to the square of the error input inasmuch as both armature and field currents are controlled simultaneously and brought up from zero together. This is a special type of control -- no other examples of dual control of d-c motors were evident in the servo mechanism literature.

A second difficulty was that of writing voltage transfer functions of the magnetic amplifiers (including delay) based upon experimental observations even though the approximate formula for time constant of a magnetic amplifier was known: $\tau = \frac{R_L N_c^2}{4 f r_c N_L^2}$. This was further complicated by the changing character of the d-c motor load. If it assumed that $I_a$ = a constant = $K_7$ since it builds up so rapidly in comparison with the field, and if time delays resulting from energy storages in the

II. Cont'd

circuit are ignored

$$I_c = K_1E$$

$$I_F = K_2I_c = K_1K_2E$$

$$T = K_4I_FK_7 = K_1K_2K_4K_7E$$

$$K_5T = \frac{Jd^2\theta_o}{dt^2} + \frac{d\theta_o}{dt}$$

$$\bar{E} = \bar{\theta}_i - \bar{\theta}_o$$

Then $\frac{\bar{T}}{\bar{E}} = K_1K_2K_4K_7 = K_8$

$$K_5\bar{T} = J_s{}^2\bar{\theta}_o + f_s\bar{\theta}_o \; (J_s{}^2 + f_s)$$

$$\frac{\bar{\theta}_o}{T} = \frac{K_5}{J_s{}^2 + f_s}$$

$$\frac{\bar{\theta}_o}{\bar{T}} \times \frac{\bar{T}}{\bar{E}} = \frac{K_5K_8}{J_s{}^2 + f_s}$$

(1) $$\bar{K}G(s) = \frac{\bar{\theta}_o}{\bar{E}} = \frac{K_5\,K_8}{J_s{}^2 + f_s} = \frac{K_5K_8}{JS(S+f/J)}$$

Energy storages in the circuit create delay factors which if known can then be added to the denominator of the above equation in the form

$$KG(s) = \frac{K}{S(\tau_1S+1)(\tau_2S+1)(\tau_3S+1)} \text{ etc.}$$

If a step function $\bar{\theta}_i = A\mu(t)$ is impressed upon the above simplified system eq (1), and $\bar{E}$ is solved for, we obtain

$$\bar{E} = \frac{A(s + \frac{f}{J})}{\left(s + \frac{f}{2J} + \sqrt{\frac{f^2}{4J^2} - \frac{K_5K_8}{J}}\right)\left(s + \frac{f}{2J} - \sqrt{\frac{f^2}{4J^2} - \frac{K_5K_8}{J}}\right)}$$

which when solved for E (t) gives

$$E(t) = \frac{Ae^{-\frac{ft}{2J}}}{\sqrt{1 - \frac{f^2}{4JK_5K_8}}} \sin\left(\lambda - \omega_n t\sqrt{1-\rho^2}\; u(t)\right) + \frac{2Ae^{-\frac{f}{2J}t}}{\sqrt{\frac{K_5K_8J}{f^2} - 1}} \sin\left(\omega_n t\sqrt{1-\rho^2}\right) u(t)$$

This of course indicates exponentially damped oscillations of varying degree and duration depending upon the particular system constants.

Applying final value theorem:

$$\lim_{t \to \infty} f(t) = \lim_{s \to 0} s\,F(s)$$ we find

final $E = 0$

The frequency of oscillation $\omega$ of the above indicated error before complete damping is

$$\omega = \omega_n\sqrt{1 - \zeta^2} \quad \text{where } \zeta = \frac{f}{2J\omega_n}$$

Solving this in terms of observed constants of the system gives:

$\omega = .354$ rad/sec. This value of $\omega$ is in fairly close agreement with the observed value of approximately 1.1 radian/sec observed by Brush Recorder and at least points toward the possibility of future mathematical analysis of this system.

# I. RESULTS

## A. System Characteristics

### 1. Steady State Torque and Speed Characteristics (Basic System).

Refer to page 18, Figuring Book #41505 for data.
The following curves are plotted:

Antenna Speed vs. Torque -- Curve 1
Armature Current vs. Torque -- Curve 2
Armature Terminal Voltage vs. Torque -- Curve 3
Armature Terminal Voltage vs. Control Current -- Curve 4

### 2. Magnetic Amplifier Transfer Characteristics

Refer to page 8 - 10 Figuring Book #41505 for data.
The following curves are plotted:

Field Current vs. Control Current (Static) -- Curve 5$^{a}$

Armature Current vs. Control Current (Static) -- Curve 5a

Armature Current vs. Control Current (Dynamic) -- Curve 5a

## B. Phase Detector and D-C Amplifier Characteristics

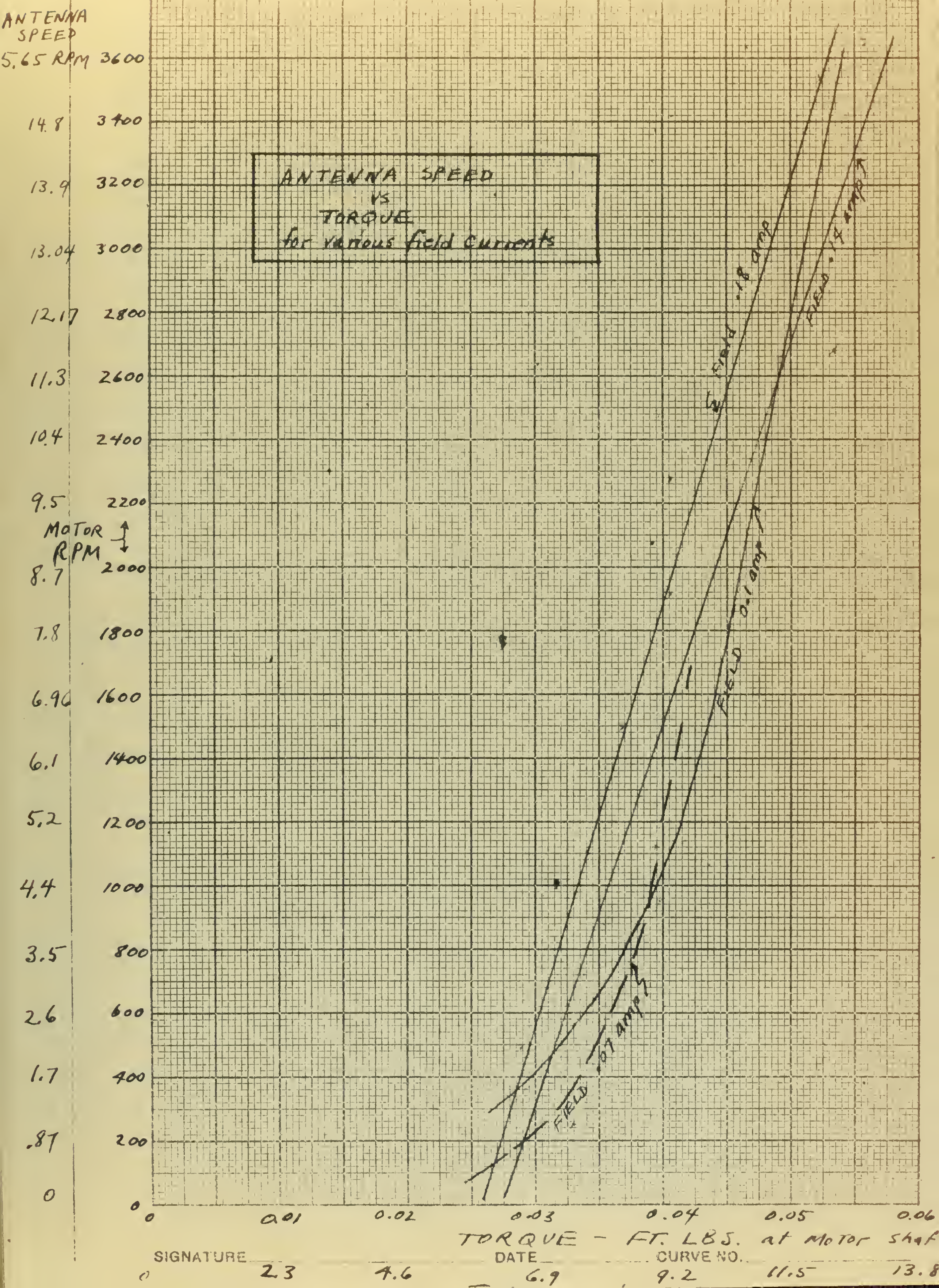
Control current versus signal input for this unit was found to be fairly linear as indicated in Curve 5b. Complete switching from maximum current output of one side of the d-c amp. to maximum current output of the opposite side was observed to occur in less than a degree movement of the 3 MCT rotor through the zero position. This was considered quite satisfactory.

## C. Results of Experimental a-c lead nets.

It was found the difficulty was encountered constructing a network which would center at the carrier frequency without adjustment. Furthermore the steepness of the slope for the sideband frequencies attempting to correct for created a problem of very small working "notch width." (In the neighborhood of 1 to 3 cycles). For this reason networks of lesser lead time were constructed as previously mentioned. However no improvement was noted. Possible improvement, furthermore, was masked at this time, by troubles of RF pickup in the synchro leads to the antenna which was located about 20' outside the building (S Building, Plant 4). All leads were replaced with shielded leads but this did not eliminate problem to any extent. The distrubing frequency was approximately 900 KC.

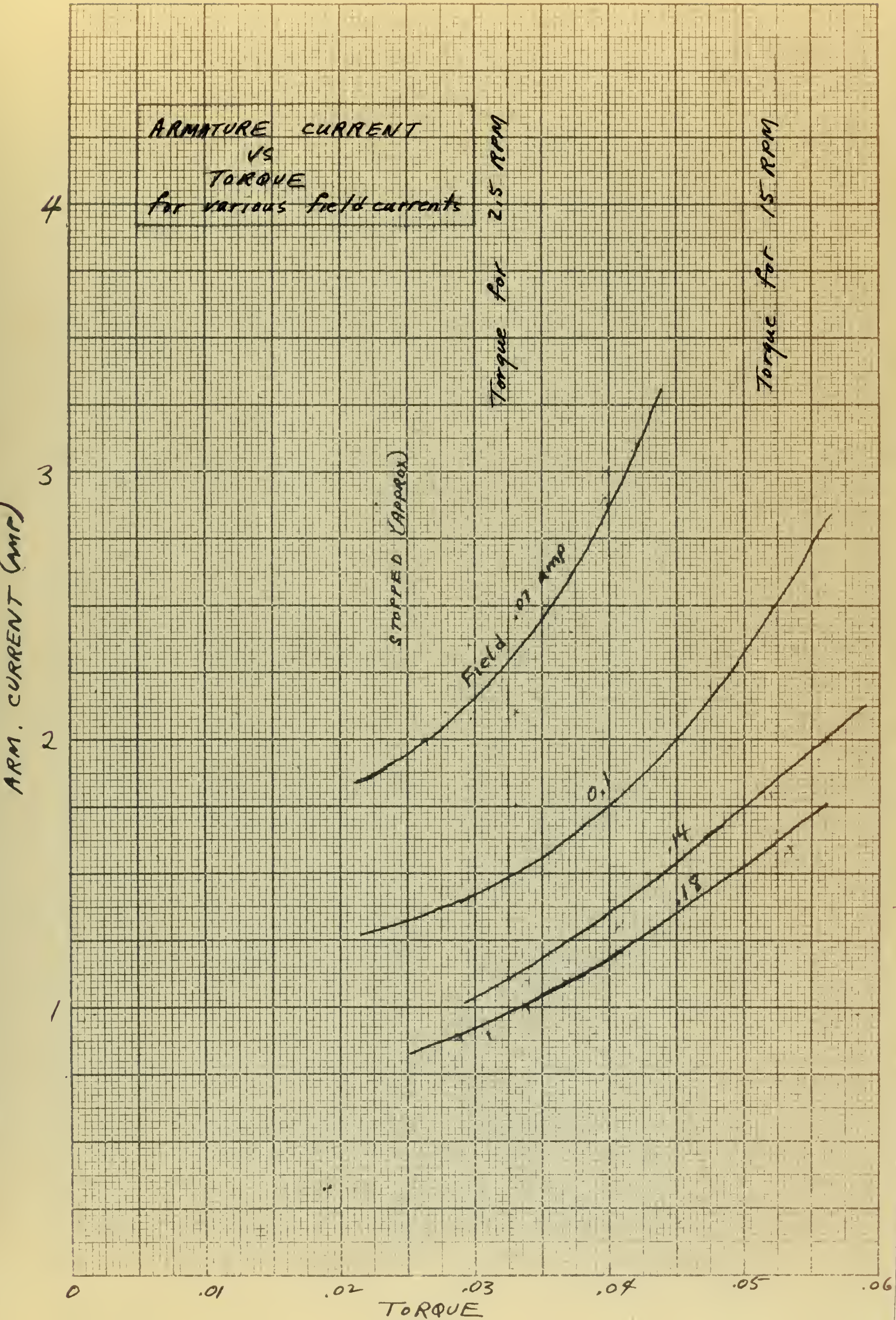
WESTINGHOUSE ELECTRIC CORPORATION

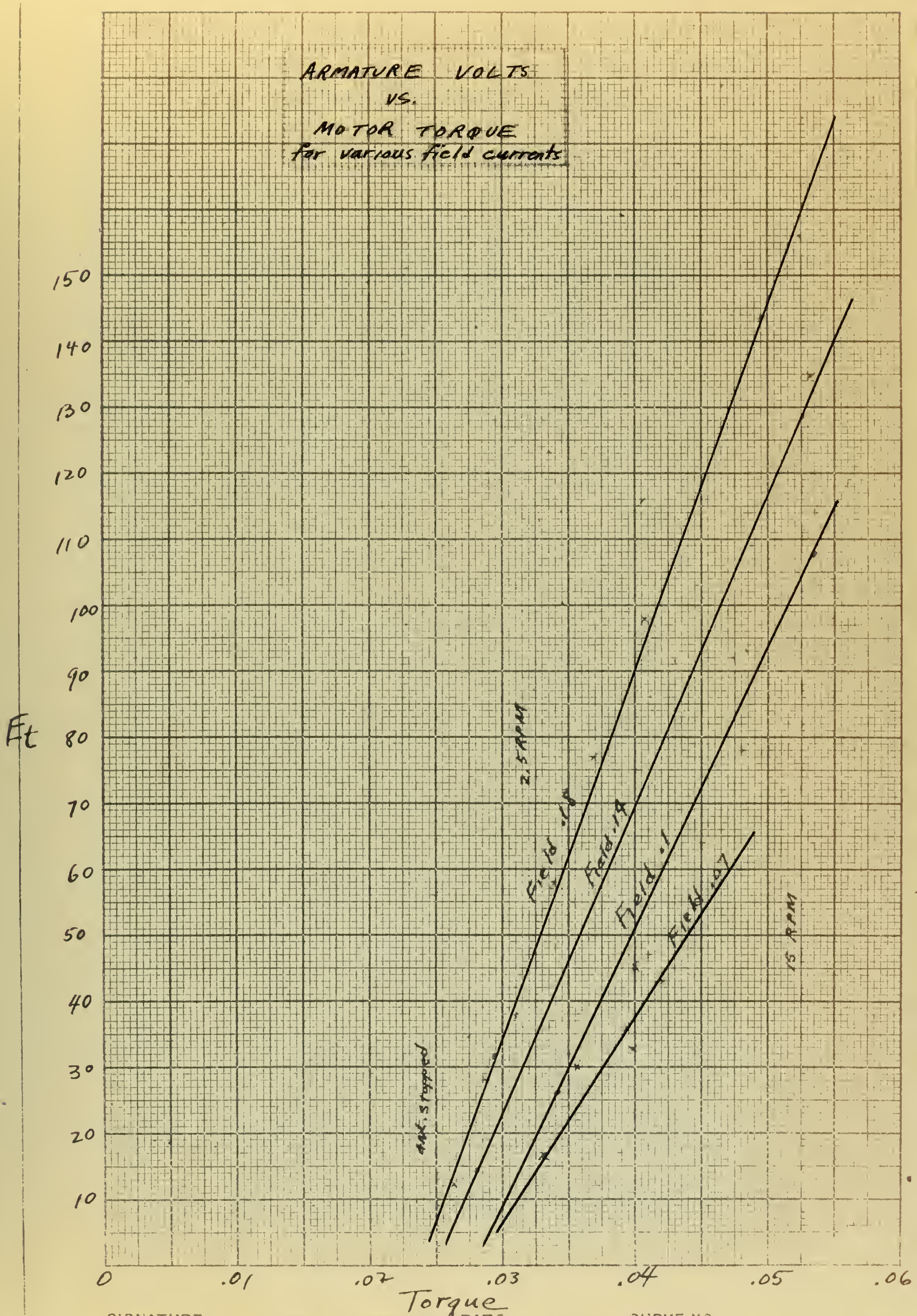
CURVE NO. 1



SIGNATURE
DATE
CURVE NO.

CURVE NO. 2

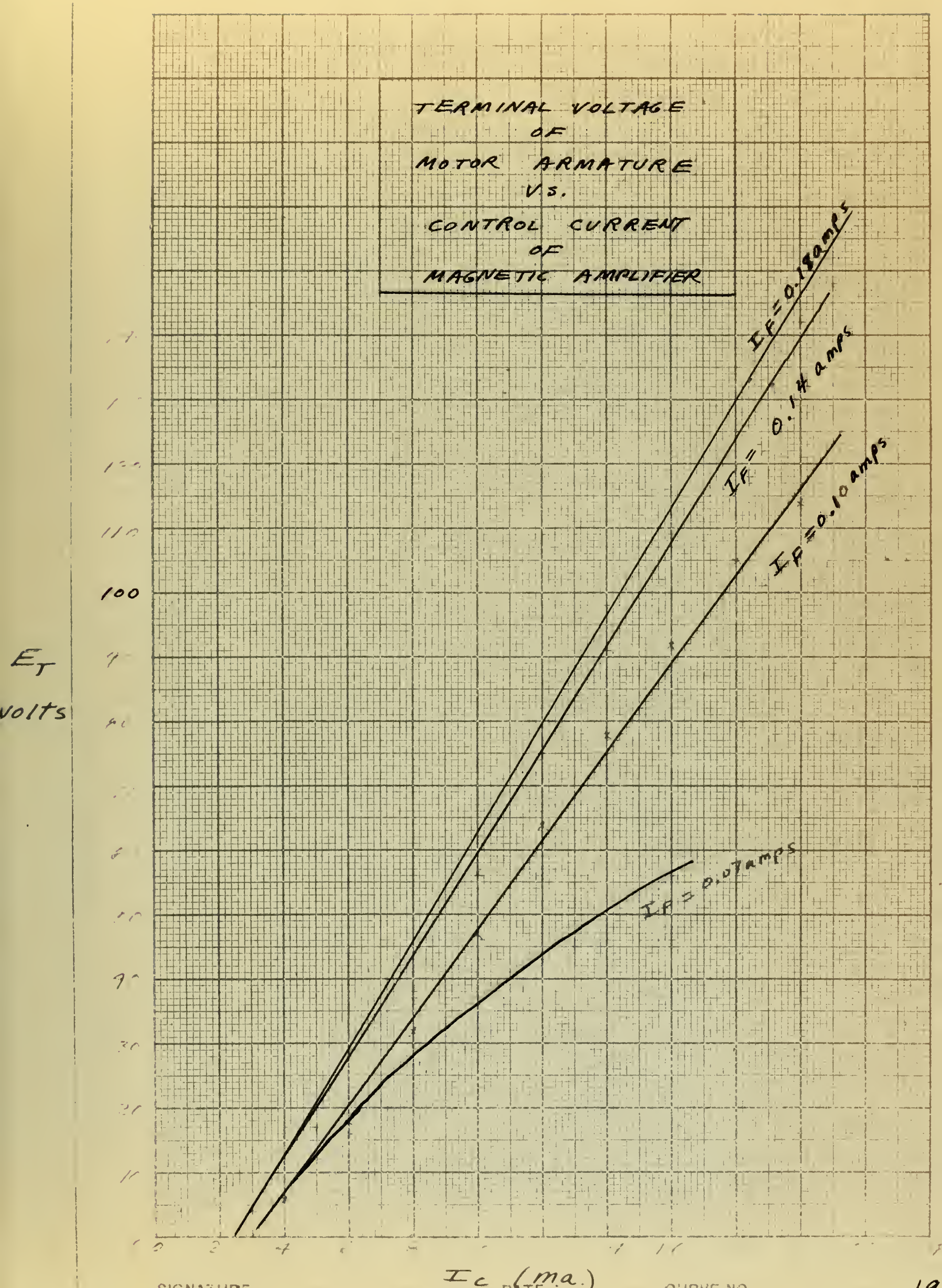

ARMATURE CURRENT
VS
TORQUE
for various field currents
Torque for 2.5 RPM
Torque for 15 RPM
STOPPED (APPROX)
Field .07 Amp
0.1
.14
.18
ARM. CURRENT (AMP)
TORQUE
4
3
2
1
0
.01
.02
.03
.04
.05
.06



ARMATURE VOLTS
VS.
MOTOR TORQUE
for various field currents

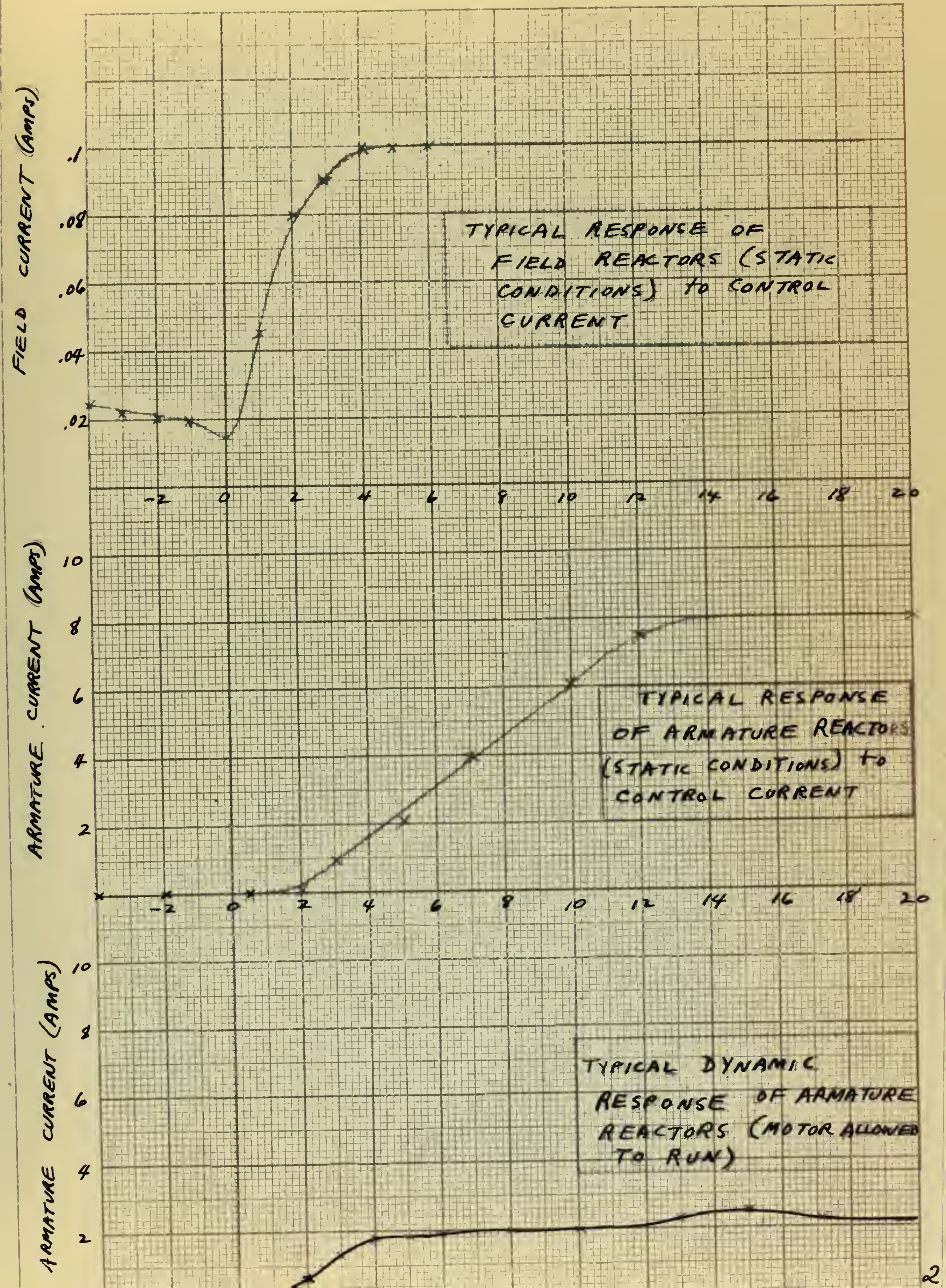
WESTINGHOUSE ELECTRIC CORPORATION

CURVE NO. 4

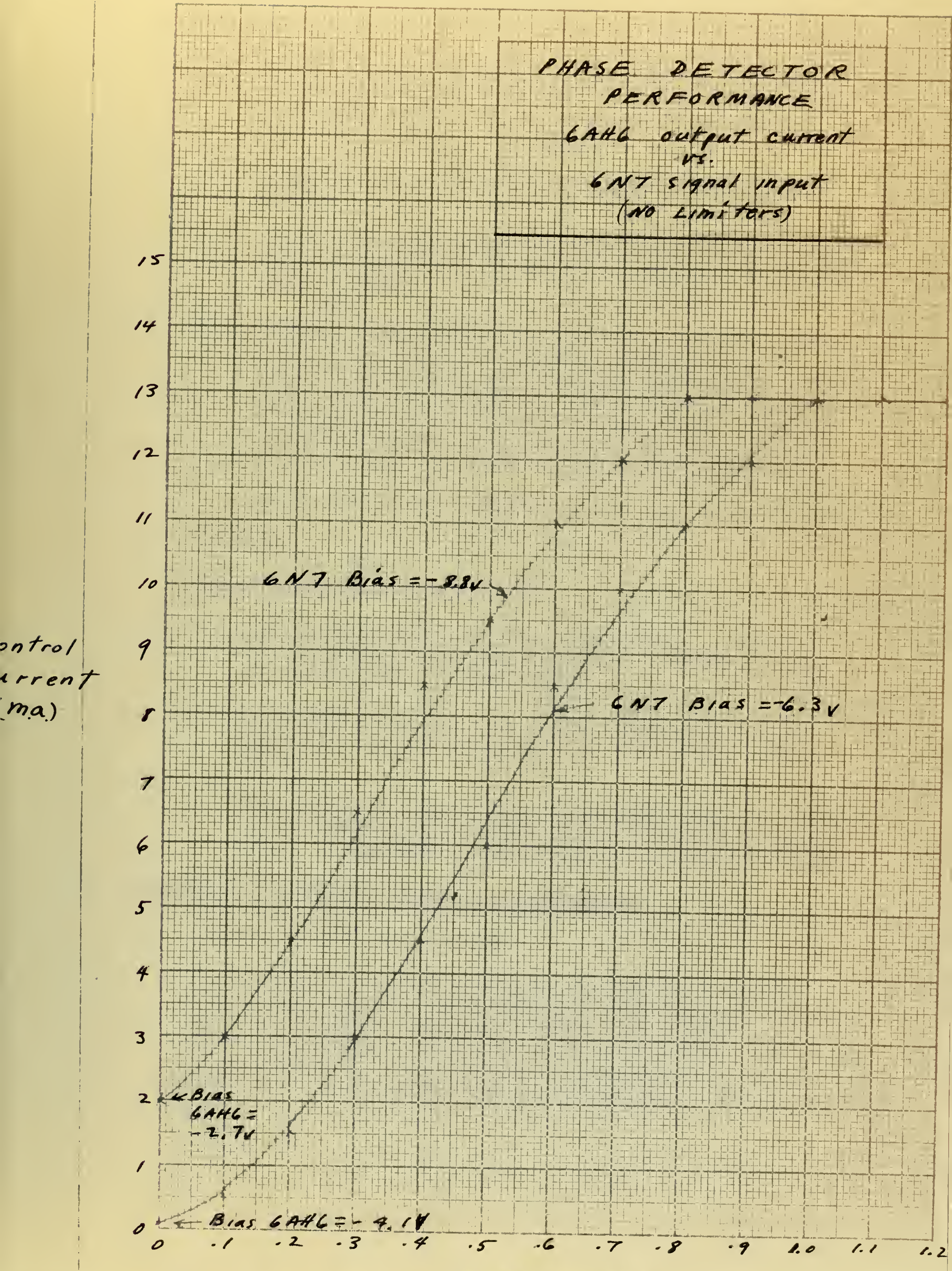


WESTINGHOUSE ELECTRIC CORPORATION

CURVE NO. 5a



CURVE NO. 5b



PHASE DETECTOR PERFORMANCE

6AH6 output current vs. 6N7 signal input (No Limiters)

SIGNATURE

CURVE NO.

## III. D. Results of Transient Measurement

### 1. Measurements

a. Field current build-up indicated by voltage appearing across a 94 ohm resistor immediately in series with a field coil is shown in the following table. (Table 1).

b. Armature current build-up is also tabulated. (Table 2).

c. Phase detector delay was measured visually with scope as .009 sec. (refer to page 21, Figuring Book #41505).

d. Overall time delay for various conditions from step application to initial reaction of the error voltage was measured visually also using scope (ref. page 23, Figuring Book #41505). Fastest feasible reaction time occurred with Magnetic Amplifier biases set to give .75 amps initial armature and .05 amps initial field current.

Delay for these conditions was 144 milliseconds.

### 2. General

The photographs reveal that

a) The greater part of the time delay is result of the field circuit; that the armature delay is negligible in comparison.

b. That the delay in the field circuit magnetic amplifier is at least 50% of the field circuit delay.

c. That magnetic amplifier time delay can be reduced by increasing the final value of field current; i.e., decreasing resistance in the field circuit.

## E. Results in reducing delay in controller

### 1. Faster Initial Conditions

The operation of the complete system in a closed loop using initial bias settings for fastest response was considerably improved except for slight oscillation remaining. However, the oscillation was still unacceptable at gain settings necessary for small positional dead space and quick response of the antenna.

# FIELD BUILDUP

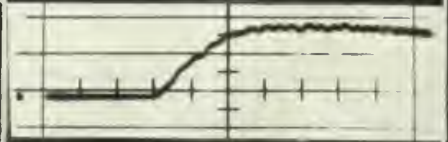
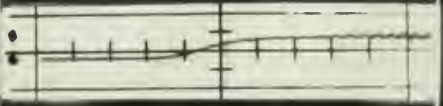
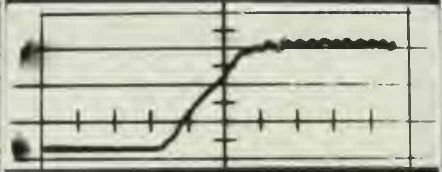
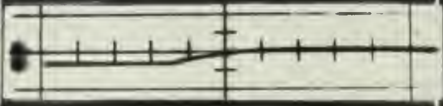
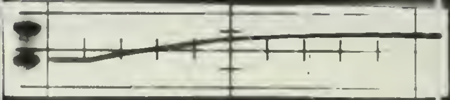
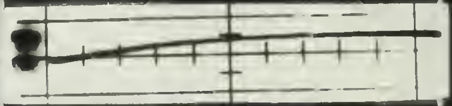
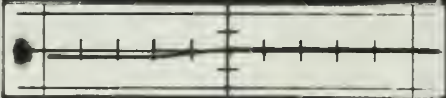
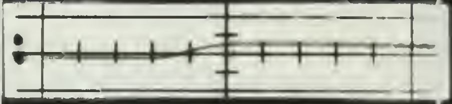
| ARM. POT. SET. | FIELD POT SET | INITIAL | | FINAL | | ms/cm | OSC. CONN. | DELAY TIME TO START | TIME FOR BUILD-UP | TOTAL DELAY m.s. | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | $I_f$ | $I_a$ | $I_f$ | $I_a$ | | | | | | |
| 30 | 40 | .05 | .75 | .11 | 1.9 | 40 | Amp. | 120 | 104 | 224 |  |
| 40 | 75 | .05 | .75 | .23 | 1.0 | 40 | Plates | 140 | 80 | 220 |  |
| 30 | 40 | 0 | 0 | .11 | 1.6 | 40 | Amp. | 132 | 100 | 232 |  |
| 30 | 40 | 0 | 0 | .11 | 1.5 | 40 | Plates | 140 | 88 | 228 |  |
| 30 | 40 | 0 | 0 | .2 | 1.0 | 20 | Plates | 24 | 96 | 120 |  |
| 30 | 40 | .05 | .75 | .2 | 1.0 | 20 | Plates | 4 | 108 | 112 |  |
| 30 | 40 | .05 | .75 | .11 | 1.5 | 40 | Plate | 124 | 82 | 206 |  |
| 100 | 60 | .05 | .2 | .2 | 1.0 | 40 | Plates | 130 | 70 | 200 |  |

TABLE 1

ARMATURE BUILDUP

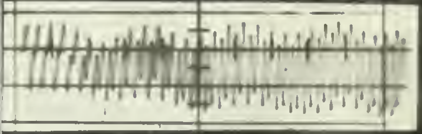
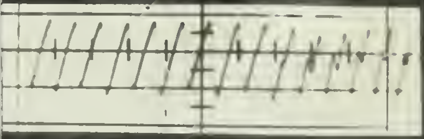
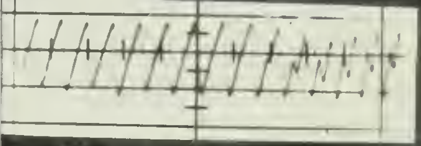
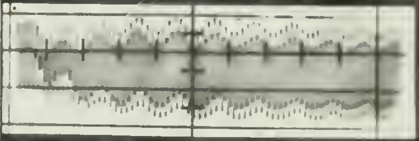
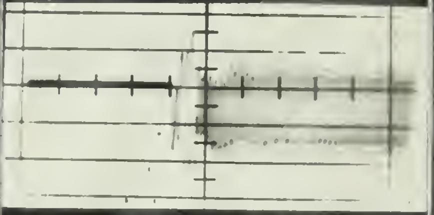
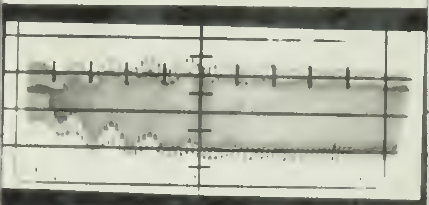
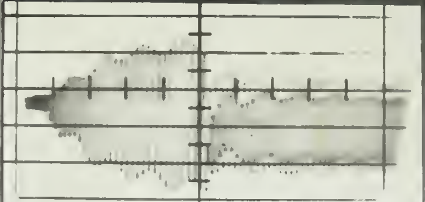
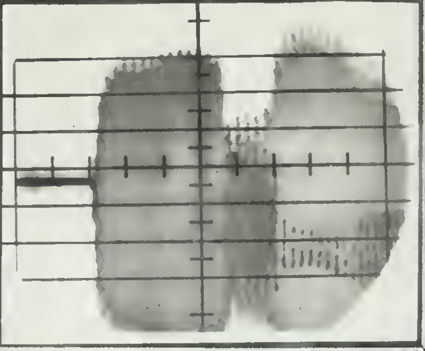
| ARM. POT. SET. | FIELD POT. SET. | INITIAL | | FINAL | | ms/cm | OSC. CONN. | DELAY TIME TO START | TIME FOR BUILD-UP | TOTAL DELAY ms. | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | $I_f$ | $I_a$ | $I_f$ | $I_a$ | | | | | | |
| 30 | 40 | .05 | .75 | .2 | 1.0 | 6 | AMP. | 7.2 | 7.8 | 15 |  |
| 30 | 40 | .05 | .75 | .2 | 1.0 | 3 | AMP | 21.6 | – | – |  |
| 30 | 40 | .05 | .75 | .2 | 1.0 | 3 | AMP | 21.0 | – | – |  |
| 30 | 40 | .05 | .75 | .2 | 1.0 | 15 | AMP | 10.5 | 33 | 43.5 |  |
| 30 | 40 | 0 | 0 | .2 | 1.0 | 15 | AMP | 57 | 9 | 66 |  |
| 30 | 40 | .05 | .075 | .2 | 1.0 | 15 | Plates | 10.5 | 35 | 45 |  |
| 30 | 40 | 0 | 0 | .2 | 1.0 | 15 | Plates | 72 | 4.5 | 76.5 |  |
| 100 | 60 | .05 | 0 | .22 | 1.1 | 70 | Plates | 133 | 7 | 140 |  |

TABLE 2

## 2. Exact a-c lead network

The network constructed to compensate for fastest response of system (144 ms) failed to work because the phase detector was unoperative as a result of harmonic and other spurious frequencies in the error signal being amplified to a considerably greater degree than the carrier and sidebands. This upset the desired operation of the phase detector. Use of the best low pass filter which would be designed, while attenuating the harmonic frequencies greatly, did not reduce them enough to eliminate this blocking action of the phase detector. For instance, for small error signals using LP filter, the relative amounts of carrier 2nd, 3rd, and 4th harmonic frequencies being impressed on the phase detector were approximately 1, 0.4, 3.8, and 0.9 respectively.

Curves numbers 6 and 7 show the Phase and gain characteristics respectively of the Parallel "T" network used and indicate plainly the difficulties referred to above. The amplifier used in conjunction with the network was essentially flat over the range investigated.

Harmonic analysis, using a General Radio Harmonic Analyzer, revealed the following impurity of the error voltage:

For minimum signals: .05 volts "RMS"

| Frequency | Relative Amplitude |
|---|---|
| 60 cycles | 74% |
| 120 cycles | 58% |
| 180 cycles | 100% |
| 240 cycles | 33% |
| 300 cycles | 34% |
| 360 cycles | 8% |
| 420 cycles | 12% |
| 480 cycles | 2% |
| 540 cycles | 24% |
| 600 cycles | 3% |
| 660 cycles | 18% |

Remainder negligible

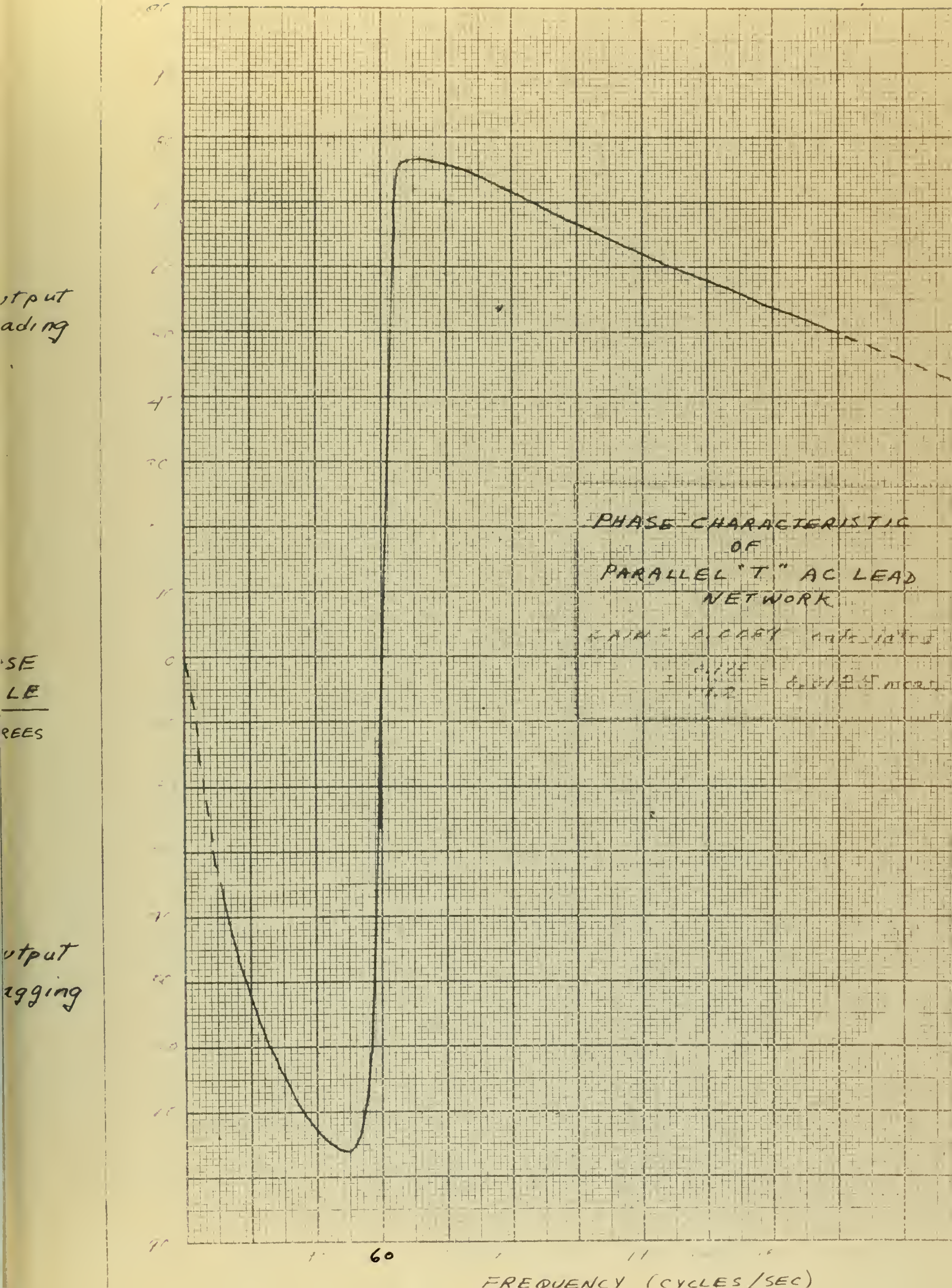
For IV "RMS" Output of error synchro

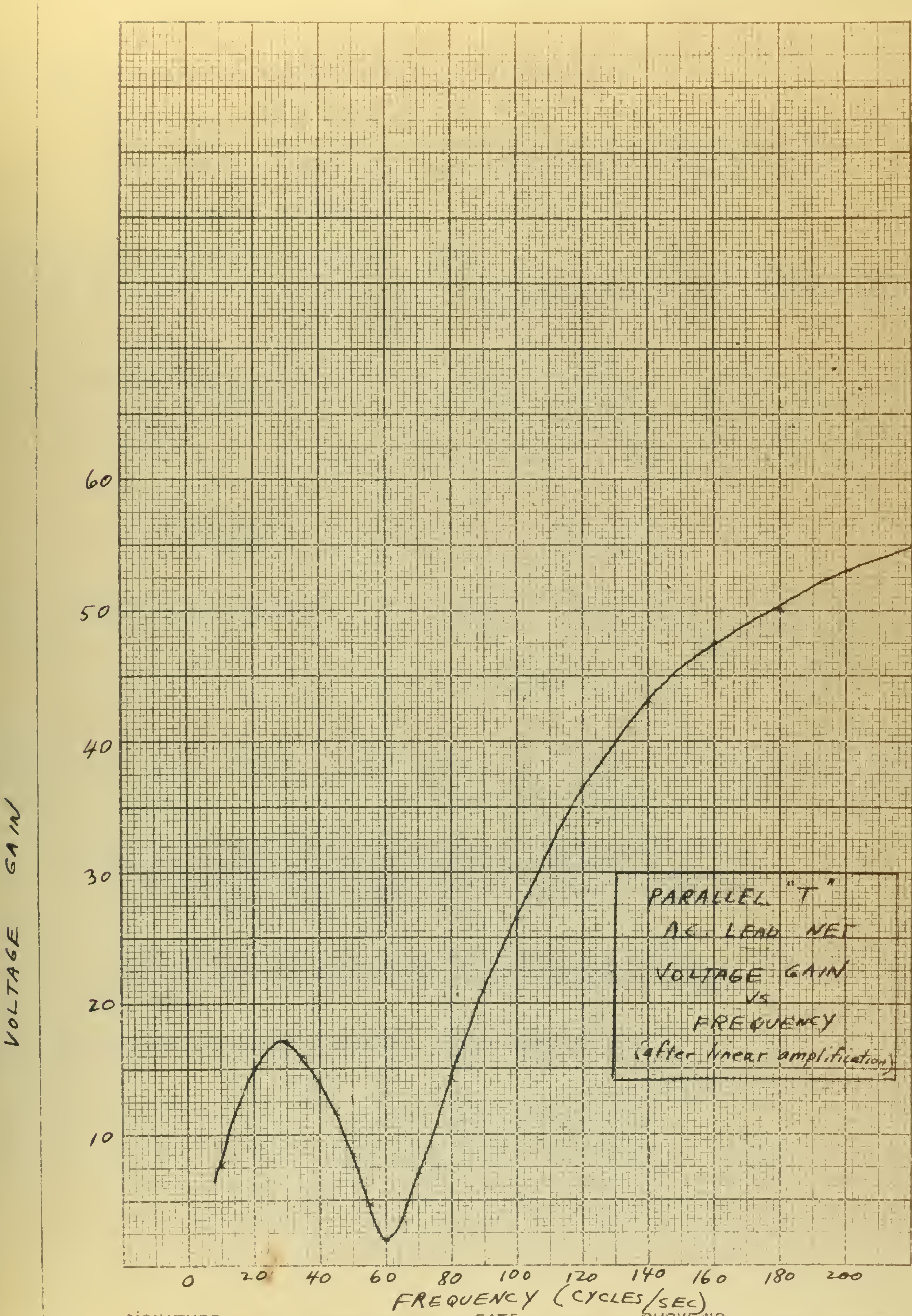
| Frequency | Relative Amplitude |
|---|---|
| 60 cycles | 100% |
| 120 cycles | 2% |
| 180 cycles | 6% |
| 240 cycles | 1% |
| 300 cycles | 2% |

Remainder negligible

WESTINGHOUSE ELECTRIC CORPORATION

CURVE NO. 6

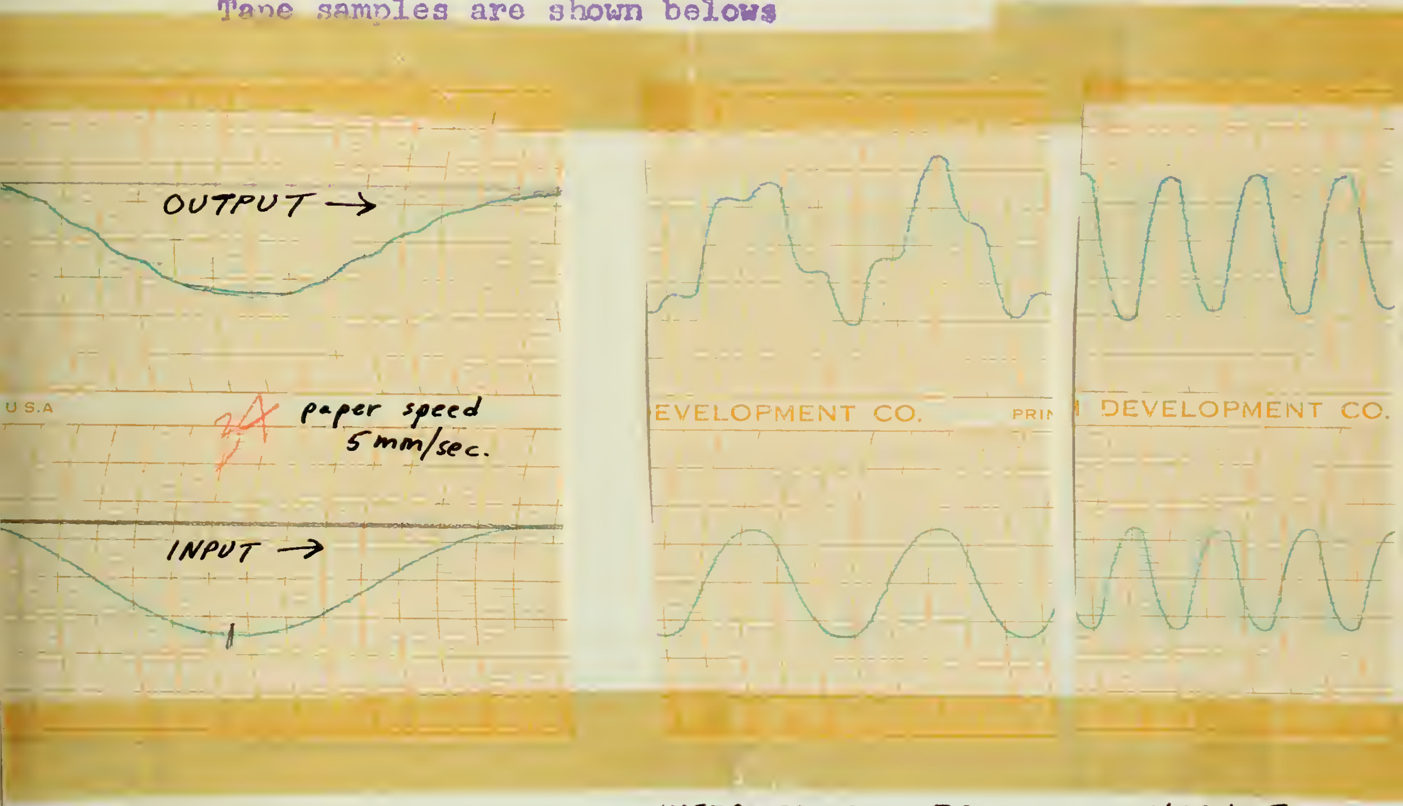



PARALLEL "T"
A.C. LEAD NET
VOLTAGE GAIN
vs
FREQUENCY
(after linear amplification)
VOLTAGE GAIN
60
50
40
30
20
10
0
20
40
60
80
100
120
140
160
180
200
FREQUENCY (CYCLES/SEC)

## III. F. Results of Frequency Response Analysis

1. Brush recording data indicates that the system follows the input fairly well, especially at the higher response frequencies. There is some "lumpiness" of the output trace at the lower frequencies apparently caused by the tendency to oscillate.

   Tape samples are shown below:

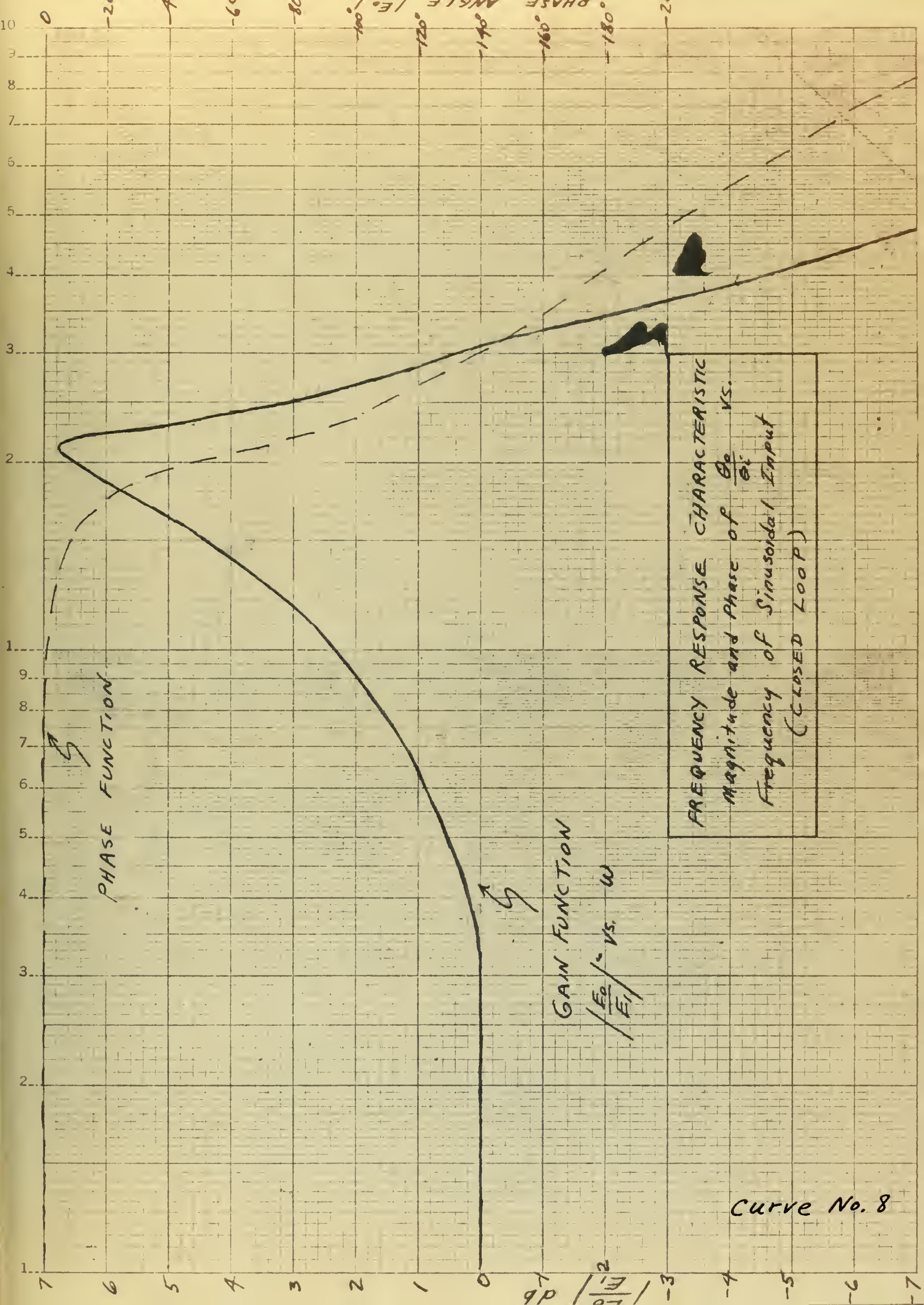


LOW FREQUENCY INTERMEDIATE FREQ. HIGH FREQ.

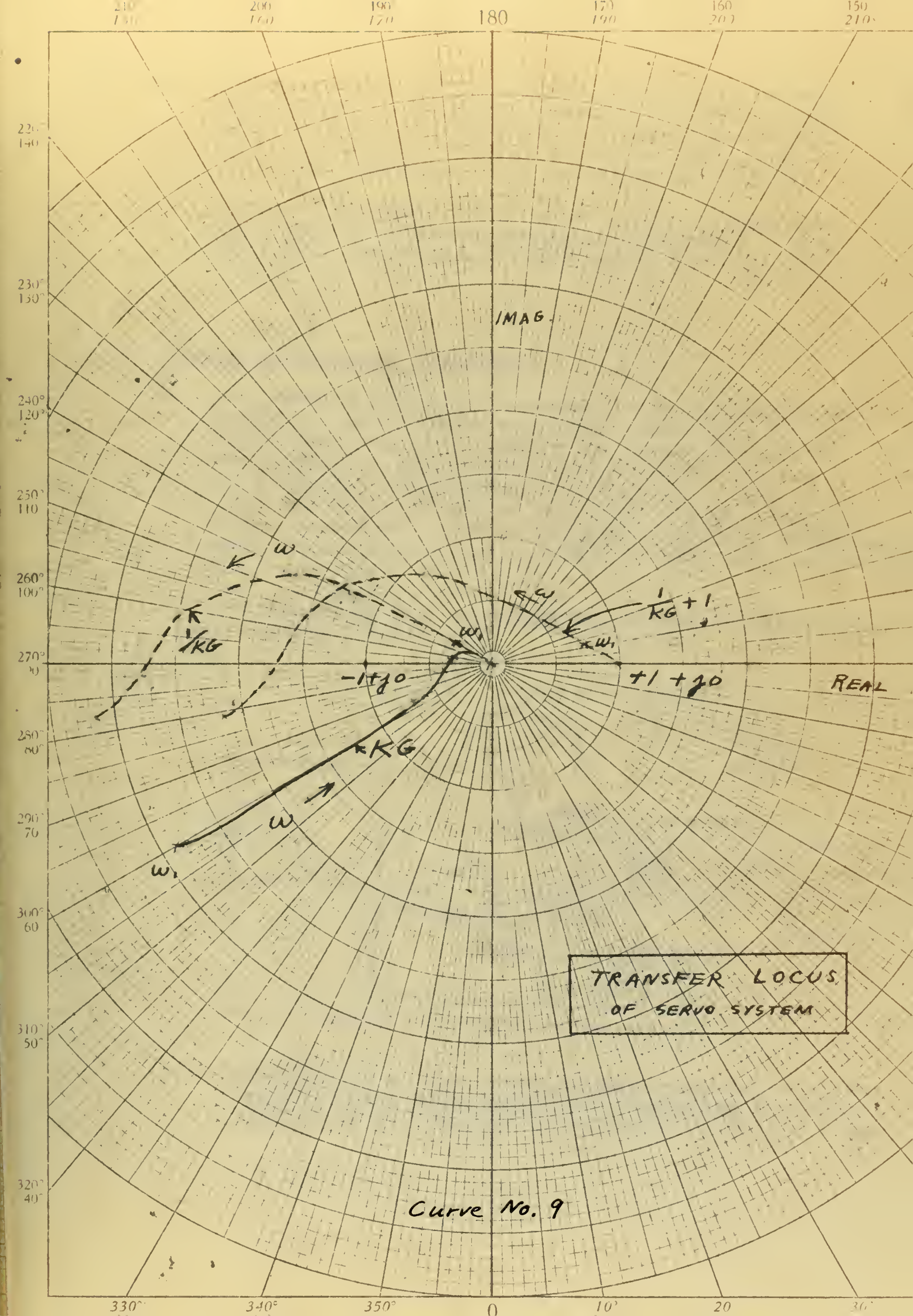
2. Magnitude and phase relations of input and output are indicated in curve number 8. Refer to page 32 of figuring book #41505 for tabulation and computation of curve data from tapes.

   It is noted that the response follows a fairly standard pattern and therefore has good possibilities of correction.

3. The KG locus is shown in curve number 9.


FREQUENCY RESPONSE CHARACTERISTIC
Magnitude and Phase of $\frac{\theta_o}{\theta_i}$ vs.
Frequency of Sinusoidal Input
(CLOSED LOOP)
PHASE FUNCTION
GAIN FUNCTION
$\left|\frac{E_o}{E_1}\right|$ vs. ω
PHASE ANGLE
0
-20
-40
-60
-80
-100°
-120°
-140°
-160°
-180°
-200
7
6
5
4
3
2
1
0
-1
-2
-3
-4
-5
-6
-7
db
10
9
8
7
6
5
4
3
2
1
9
8
7
6
5
4
3
2
1

Curve No. 8



TRANSFER LOCUS OF SERVO SYSTEM

Curve No. 9

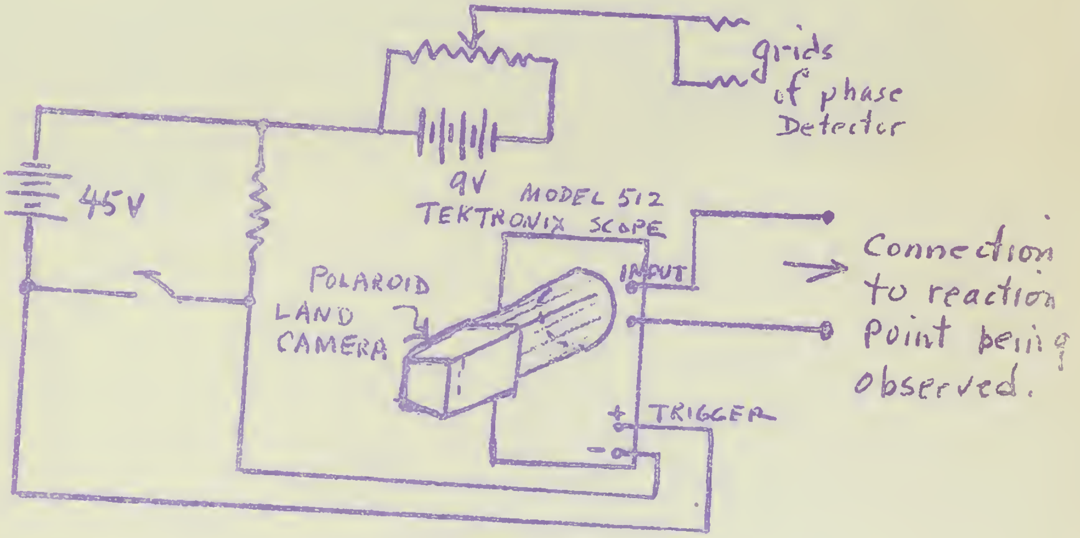
III. G. Use of the d-c compensating network showed marked improvement in observed response of system. Lack of time, however, prevented refinement and adjustment of the d-c networks as well as taking of additional necessary data on frequency response.

It was noted that higher gains could be used and that final positional error was negligible. Also the "dead space" using higher gains was negligible.

## IV. Special Measurement Techniques

A. Considerable time was consumed in the assembling of necessary servo system measuring equipments and the design of circuits to complement these equipments. The particular difficulties encountered were the low frequency measurement requirements -- d-c to 60 cycle and the problems of 60 cycle carrier amplification. Therefore a few of the more important techniques used are enumerated for possible future servo laboratory use.

1. Arrangement for measuring transients resulting from impulse function:


grids of phase Detector
9V
45V
MODEL 512 TEKTRONIX SCOPE
INPUT
POLAROID LAND CAMERA
Connection to reaction point being observed.
+ TRIGGER
-

The closing of the switch triggers the trace of the "scope" whose sweep stability adjustment has been reduced to just beyond the point of automatic trig-

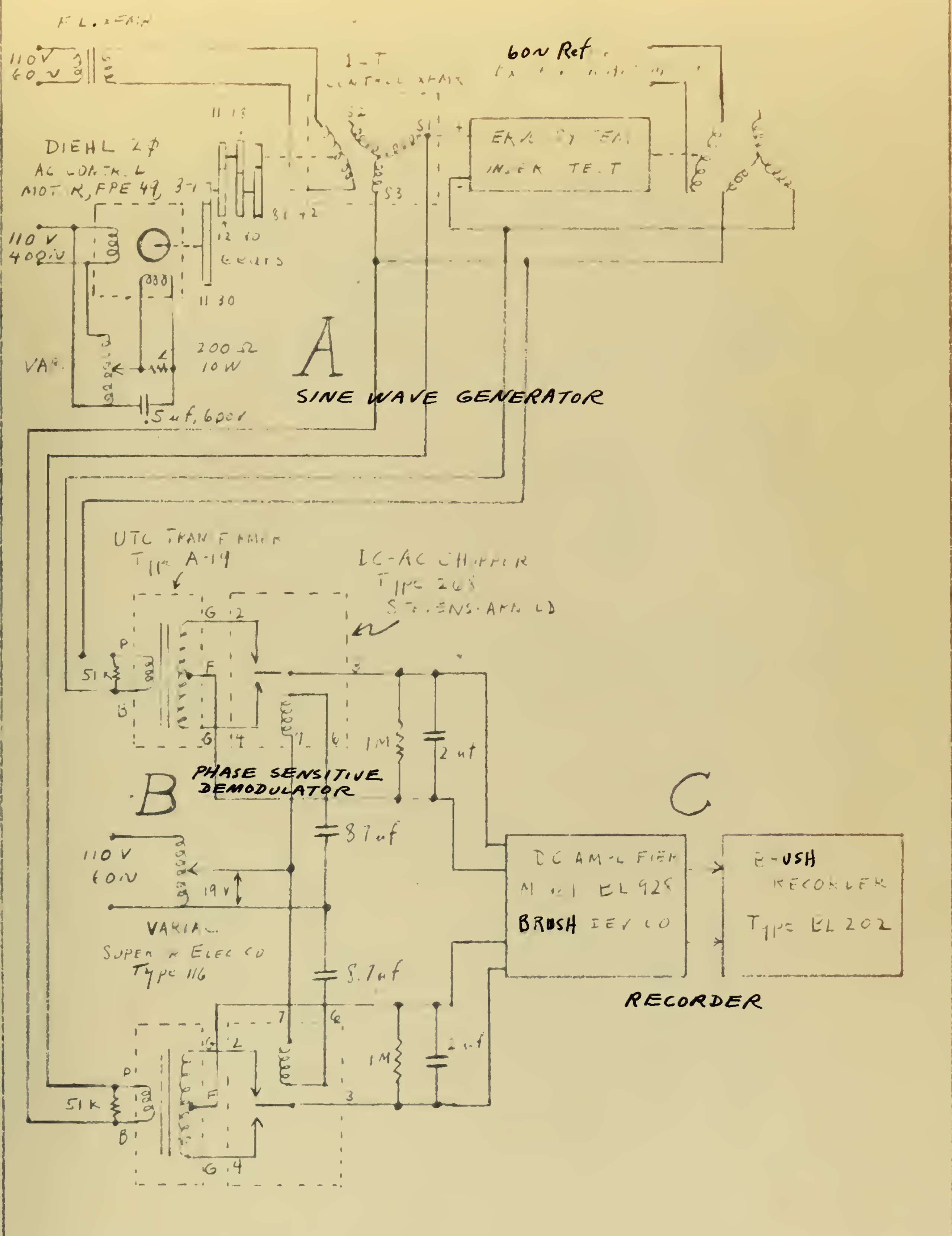
gering. Simultaneously the 6N7 of phase detector is cut off starting impulse reaction through system. This particular model of "scope" was the only one which could be found with a slow enough sweep. The camera shutter was opened and remained in darkness of the adapter until the scope had been triggered. After the single transient was observed through the eyepiece to cross "scope", the shutter was closed. The developed picture was then available in approximately 1 minute. This was extremely convenient.

2. The method of frequency response measurement used is shown in Figure 9. It is believed that this is the most powerful method of servo analysis. Results are clear and time necessary for analysis small once equipment has been assembled.

3. Method of synchronizing chopper in phase-sensitive modulator-demodulator.

   In the frequency response method described above, the chopper must be synchronized with the carrier frequency in order that it "chop" the unwanted halves of the modulation envelope so that the desired halves can be demodulated to give a pure sine wave as in Figure 10.

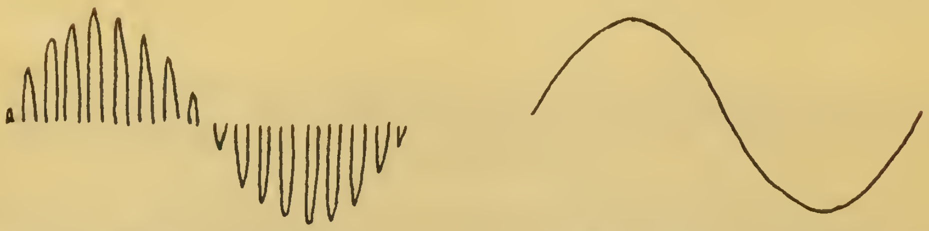
   In order to synchronize, a d-c voltage of from 0-50 V. must be impressed upon the d-c or demodulated output terminals of the demodulator. The a-c output of the unit is then a square wave which may be compared phasewise with the reference voltage. A variable capacity C, in series with the chopper coil is adjusted so that the Lissajons pattern appears as shown, indicating proper synchronization.



EXPERIMENTAL ARRANGEMENT TO MEASURE FREQUENCY RESPONSE OF SERVO SYSTEM (USING 60~ SYNCHROS)

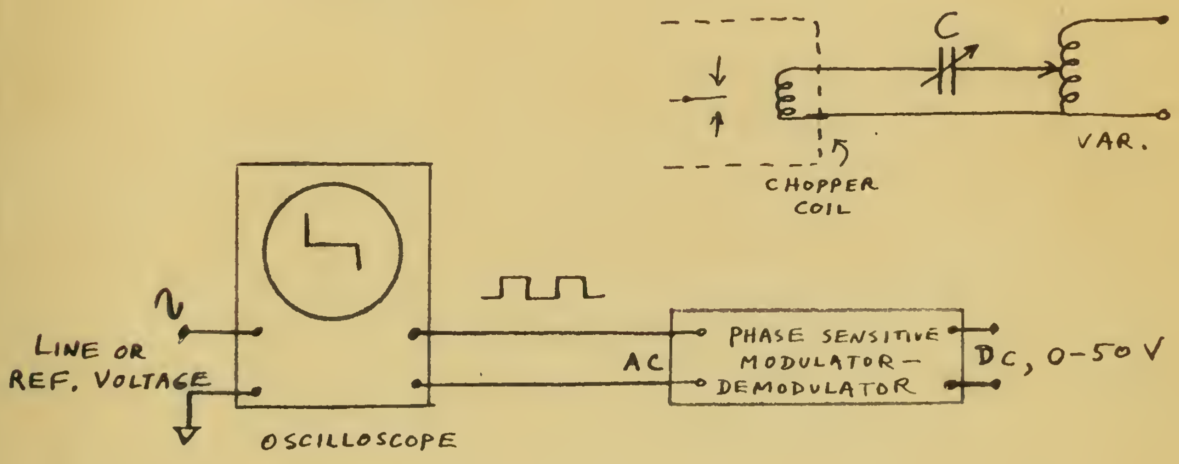
FIGURE 9

# SYNCHRONIZATION OF CHOPPER

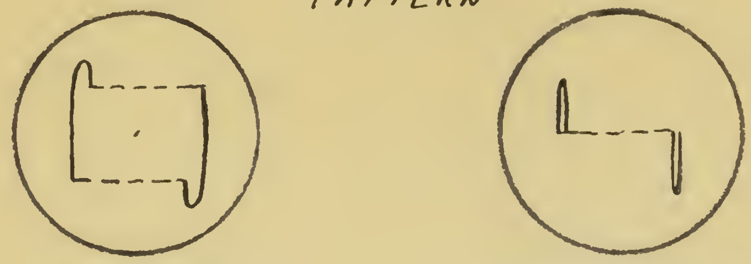


DESIRED CHOPPER OUTPUT

AFTER DEMODULATION



LISSAJOUS PATTERN



OUT OF PHASE

SYNCHRONIZED

FIGURE 10

B. Techniques recommended for future use:

1. A method of measuring the stall torque characteristics of the motor or motor system while loaded. Stall torque curves were never obtained for this particular motor and this was considered a handicap in analysis.

2. Possible use of mechanical method (scotch yoke) of imparting a sinusoidal input of varying frequency to the input of a servo system.

3. Use of oscillator for applying triangular inputs (ramp functions), step functions and sine waves of low frequency to the input of a servo system.

## V. Conclusions

A. The system as it now stands with partially operative d-c compensating networks is still somewhat erratic although the oscillatory action has largely been reduced. It has the advantage of high gain and zero positional error after it reaches the new position. If the project is continued, the following are recommended to improve the system performance.

1. The use of feedback and greater gain in the field circuit in order to reduce substantially the time delays in the system.

2. Further frequency analysis, now that the system is fairly well stabilized at higher gain. This would probably reveal the correct adjustment to make in the present lag-lead networks.

3. Further study to adapt the system itself to the best use of d-c compensating networks inasmuch as a-c networks have proved unacceptable and only a preliminary d-c network is now in use.

4. Further study of the magnetic amplifiers themselves, the object being determination of origin of certain irregularities of operation which occasionally presented themselves, particularly in regard to bias settings.

At this writing there is no positive assurance that the system can be made satisfactory for the use intended. There is a good possibility that it can but the worth of continuing the project should be dictated by the relative value and importance of other pending projects.

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